

AERODYNAMIC DRAG LOSS CHARGEABILITY AND ITS IMPLICATIONS IN THE VEHICLE DESIGN PROCESS

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Abstract

The purpose of this paper is to explore the nature of aerodynamic drag losses, relate them to aerothermodynamic losses in the aircraft as a whole, and develop methods for assessing drag chargeability. The concept of the aerodynamic “loss deck” is introduced and applied to the analysis of an F-5E fighter. It is shown that this loss deck can be used to integrate aero losses through the vehicle mission to obtain total losses attributable to each drag mechanism. This information is then used to facilitate design trades and estimate sensitivity factors useful in the design process.

Introduction

Aerodynamic configuration is one of the most important aspects of aircraft design. Ample proof of this fact is afforded by any of the hundreds of designs that failed because their creators ignored or were ignorant of good aerodynamic design practice. The reason for the importance of aerodynamics is simple: aerodynamic drag and engine inefficiency are the two primary sources of loss for an aircraft. As a result, they are strong drivers on fuel load required to complete a mission and by extension, strong drivers on overall vehicle size and cost.

The definition of aerodynamic loss for most vehicle designs is relatively clear-cut, though some discussion is offered on this point. The primary contribution of this paper is the development and application of the concept of an aerodynamic “loss deck” that gives detailed knowledge of aerodynamic loss and facilitates its use in the larger context of vehicle design trades. The development of this loss deck is tailored such that aerodynamic losses can be partitioned for maximum usefulness when applied in a loss management model.^{1,2,3} However, it will be shown that the aerodynamic loss deck has value in and of itself when used as an analysis tool to understand the sources of aerodynamic loss.

Since the best way to convey knowledge is often by example, this paper also includes an application of these methods to the F-5E fighter aircraft. This will start with a discussion on the aerodynamic analysis methods and tools used to model the F-5E and a validation of their accuracy. This will culminate in the development of an aerodynamic “loss deck” for the F-5E.

Aerodynamic Loss Estimation

As previously mentioned, the definition of aerodynamic loss is regarded by most to be well-defined and subject to little debate. It is generally thought of as the conversion of vehicle kinetic energy into useless forms of energy such as frictional heating. For the sake of precision, aerodynamic loss is taken in this discussion to mean *the reduction in total vehicle work potential due to irreversible fluid-dynamic interactions between the vehicle and the atmosphere.*[†]

Aerodynamic loss is typically due to the action of fluid dynamic drag upon the aircraft, which is the mechanism by which kinetic energy of the vehicle moving through the atmosphere is deposited into the atmosphere in the form of a momentum deficit, and ultimately, as heat. There are several physical transport mechanisms that are responsible for this movement of energy, but they all manifest themselves in the same manner: drag. Since drag is a force that acts on the vehicle as it moves through the atmosphere, drag work follows directly from the textbook definition of work as force acting through a distance:

$$\text{Drag Work} = \text{Drag} * (\text{Flight Velocity}) * (\text{time}). \quad (1)$$

In most situations, drag work is nearly equal to the reduction in vehicle kinetic energy (or propulsive work required to offset drag), so Eq. 1 is usually taken to be synonymous to aerodynamic loss. By this definition, calculation of aerodynamic loss is merely a matter of calculating total drag and multiplying by flight velocity and time. This is an entirely accurate and acceptable definition for aerodynamic loss in most situations, and will be used later in this paper for estimation of aerodynamic loss for the F-5E validation case.

However, before proceeding into further descriptions of aerodynamic loss analysis methods, it is important to pause for a moment to point out that Eq. 1 is not the only model for aerodynamic loss available for use. In fact, for high Mach flight conditions, the definition of aerodynamic loss given in Eq. 1 yields results that are incorrect. This statement may at first seem to be highly dubious, but its merit can be understood through a simple thought experiment.

To start, consider the simplest possible case of skin friction drag on a flat plate at zero angle of attack, as for instance, a wall in the test section of a wind tunnel.

[†] Exclusive of those occurring inside the engine inlet capture stream tube.

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Assume for argument's sake that the wind tunnel is capable of producing flows in its test section ranging from low subsonic to hypersonic speeds. Further imagine that the wind tunnel is turned on and the flow speed in the test section is increased slowly. At low subsonic speeds, if the drag force acting on a section of the wind tunnel wall is measured, it can be multiplied by the flow speed in the test section. The result is total drag work done by the wall on the flow inside the tunnel (as perceived by the observer moving with the flow field through the tunnel test section). As the speed is increased to the transonic speed regime, the situation is still very much the same as for the incompressible case. Now, as speed is further increased into the supersonic regime, the observer moving with the flow inside the test section still perceives that the wall is doing work on the flow in his frame of reference. However, there is a slight difference that is becoming increasingly evident, this being increased heat transfer from the boundary layer into the wall, and from the wall out into the laboratory environment. In any event, the drag work perceived by the moving observer is still the product of drag times flow velocity.

As the speed is further increased into the hypersonic regime, the situation becomes exacerbated. Heat flux into the wind tunnel wall increases exponentially, and the temperature at which this heat transfer occurs increases as well. Therefore, the heat that is being transferred from the wind tunnel wall into the laboratory environment has work potential. For instance, one could use the heat energy from the tunnel wall as a heat source for a boiler to create steam, which can then be expanded through a turbine to produce work. Perusal of any thermodynamic textbook quickly reveals that the maximum work that could be produced by a heat engine operating between the wall recovery temperature and ambient temperature is given by the Carnot engine, the output of which is known to be:

$$(\text{Work Potential})_{\text{FrictionHeating}} = Q_{\text{out}} \left(1 - \frac{T_{\text{Wall}}}{T_{\text{Amb}}} \right) \quad (2)$$

where Q_{out} is the total heat transfer out of the tunnel wall, T_{wall} is the wind tunnel wall temperature, and T_{amb} is the ambient temperature in the lab environment. Thus, a portion of the drag work can be recovered as heat. The work potential available due to frictional heating is given in Eq. 2 and is the fundamental difference between the exergy⁴ definition of aerodynamic loss and the simple definition given by Eq. 1. At low Mach numbers, the work potential available due to frictional heating is so small as to be negligible. However, recovery temperature increases as velocity squared while heat flux changes as velocity cubed. Therefore, the latent work potential that can be extracted from the ambient flow via heat transfer increases rapidly as flow velocity is increased.

Consequently, the definition drag work given in Eq. 1 is not a measure of aerodynamic loss, but is rather a measure of drag work that is nearly equal to aerodynamic loss at low Mach numbers. Based on Eq. 2, aerodynamic loss in high-speed flows might be better defined as:

$$\text{Aero Loss} = \text{Drag} * (\text{Flight Velocity}) - Q_{\text{out}} \left(1 - \frac{T_{\text{Wall}}}{T_{\text{Amb}}} \right). \quad (3)$$

At low speed, there is little difference between these two definitions of aerodynamic loss, but at high speed, the differences become increasingly obvious, as noted by Ackeret.⁵

To understand how this translates into practical calculation of aerodynamic loss for flight vehicles, consider another hypothetical example of a flat plate at zero incidence in a flow field. The difference between this and the previous example is that the flat plate is now part of the fuselage of a vehicle capable of cruising at hypersonic speeds. Assume again that the vehicle is slowly accelerating from low speed to hypersonic flight. Much as in the wind tunnel example, the drag loss is very nearly equal to the drag work until hypersonic speeds are reached. At these speeds, frictional heating will elevate the skin temperature to levels far higher than either the static temperature in the ambient environment surrounding the vehicle or the vehicle internal structure and fuel. Therefore, the heat flux passing through the skin of the vehicle has the potential to do work as measured relative to the external environment or the vehicle's own internal environment. Since the vehicle is immersed in a hypersonic flow, it is likely that the entire surface of the vehicle is at high temperature, therefore making it impractical to use the external atmosphere as a heat sink.[‡] The only option is therefore to use the vehicle itself as the heat sink. Specifically, the vehicle's structure and fuel have a high heat sink capacity and are at relatively low temperature. It is theoretically possible to construct the vehicle's internal systems to take advantage of the work potential produced by frictional heating to do useful work. A likely scheme would be to pass pressurized fuel near the skin surface so that net work would be produced when the fuel was heated in the skin, injected, burned, and expanded in the propulsion system. In this situation, it seems clear that not all the drag work done by the vehicle on the atmosphere becomes a loss. Instead, a portion of the work is recovered in the form of heat and re-used in the propulsion system.

The distinction between Eqs. 1 and 3 is somewhat esoteric for most applications (notably the F-5E), because the vast majority of flight vehicles never reach hypersonic flight speeds. However, there are other, more practical reasons for thinking in terms of aerodynamic work loss rather than drag. First and foremost,

[‡] A possible exception might be the case where a radiative heat transfer mechanism is available.

aerodynamic loss is directly comparable to thermodynamic loss in the engine and vehicle subsystems. Therefore losses in the propulsion system, subsystems, and aerodynamics can be compared on an “apples-to-apples” basis, contrary to today’s approach where the only way to compare the relative value between 1 count of drag to 1 point in compressor efficiency is through sensitivities. Moreover, aerodynamic loss is measured in units of power, which is a physically intuitive quantity. Therefore, a work loss figure of merit (FoM) is at least on par with a drag FoM in terms of ease of comprehension and intuitive feel for “orders of magnitude.”

The final argument for using a work loss FoM is the realization that it is likely that there are other situations in which aerodynamic work is partially converted into some other form of energy having work potential (radiation produced in the laser cavity of gas-dynamic lasers might be one example). Aerodynamic drag is of interest primarily because it represents a loss in ability to do work for most vehicle design situations. As modern aerospace systems become increasingly complex, it is likely that the more precise definition of aerodynamic loss will be required to accurately analyze these systems. Therefore, one must be careful how aerodynamic loss is defined because loss in work potential is not necessarily the same as drag work.

Aerodynamic Loss Chargeability

The discussion in the previous section defined aerodynamic loss and explained that it is not necessarily the same as drag work. This having been said, one may inquire as to the usefulness of such as concept and how it may best be applied in the vehicle analysis process. This section will explore the applications for work potential definitions of aerodynamic loss (as opposed to the more traditional force-based concept of drag) and show how work potential methods may be used to advantage in the design process by introducing the concept of aerodynamic loss chargeability.

The introductory section of this paper mentioned that aerodynamic drag is one of the two primary sources of loss in work potential for aircraft, and for this reason, is a strong driver on overall vehicle size and efficiency. Since one of the main objectives of aerospace vehicle designers is to produce vehicles that perform a function with minimum cost, it stands to reason that designers are keenly interested in minimizing aerodynamic loss.

This is usually accomplished by analyzing a design, understanding what factors are the primary contributors to aerodynamic loss (the cause-effect relationship), proposing design changes to ameliorate these losses, and re-analyzing. The cause-effect relationship between loss and its underlying drivers is always implicitly in the mind of the designer. The best designers are usually the ones who have the ability to simultaneously juggle all of these cause-effect relationships in their mind’s eye to find the best balance amongst all of them. *The idea behind the*

concept of aerodynamic loss chargeability is to explicitly and formally define the cause-effect relationships between aerodynamic loss and its underlying drivers. The result is clear visibility of what factors are driving aerodynamic loss and how much loss each is causing.

To put it another way, it is not enough to dryly observe that vehicle drag at a given flight condition is 40% wave drag, 30% induced drag, and 30% skin friction (for example). Rather, one would like to know that 25% of total aerodynamic loss at that flight condition is due to wing volume; 20% is due to wing wetted area; 25% is due to fuselage volume; 20% is due to fuselage wetted area; 10% is due to volume and wetted surface of the tails; 5% is due to fuselage weight, etc. This is information that truly illuminates the path to better design decisions.

Definition of Aerodynamic Loss Chargeability

Put simply, the concept of *aerodynamic loss chargeability* is a means for allocating all of the various components of drag to their underlying source in a way that directly links aerodynamic loss to its underlying drivers. To begin, consider the term “drag chargeability.” It seems self-evident that a component of drag should be “charged” to a functional group if, without the presence of that functional group, the drag would not exist. For example:

- Aerodynamic drag of tail surfaces is chargeable to the flight control system because it is the presence of the flight controls and the need to achieve stability through aerodynamic means that drives the need for tail surfaces.
- Aerodynamic drag of nacelles is chargeable to the propulsion system because it is the design and configuration of the propulsion system that drives the size and drag of the engine nacelles.
- Induced drag produced by the wing is chargeable to the weight of each vehicle component because induced drag is a consequence of producing lift to offset the weight of the vehicle.

The starting point for defining drag chargeability should always be the vehicle drag build-up. There are two reasons for this: first, a detailed analysis of aerodynamic drag is required for preliminary and detail design, so this information is already available to the airframer without the need to make any special effort. Second, most airframers have long ago established ground rules and guidelines for bookkeeping schemes used in estimating aerodynamic drag. These bookkeeping schemes usually group drag components according to the physical mechanisms that give rise to them (wave, friction, pressure, excrescence, etc.). This is a ready-made starting point for definition of drag chargeability.

The real challenge in defining drag chargeability is in accounting for the myriad of interactions amongst components such that the drag “blame” is distributed in a

way that is reflective of the physical features that drive each loss. Clearly, as the number and strength of aerodynamic interactions between components increases, decomposition and chargeability assignment becomes more difficult (for example, wave drag of an aircraft in supersonic flight is highly dependent upon interactions between components).

There are many valid approaches to this problem, and selection of any single approach is a matter of matching current needs for the problem at hand to a suitable chargeability scheme. This implies having a chargeability scheme with sufficient fidelity to capture germane effects and, to some extent, is also a matter of personal preference. The approach used here is to allocate drag chargeability according to the type of drag. The main interest is allocation of wave, skin friction, and induced drag chargeability. In addition, interference drag is considered briefly because of its importance in some aircraft applications, though it is not used in the F-5E loss model constructed later herein.

Skin Friction Drag Chargeability

Skin friction drag arises due to shearing of a viscous fluid in contact with a solid surface, such as the skin of a vehicle as it passes through the atmosphere. Because skin friction acts on the wetted surfaces of the vehicle, it is obvious that wetted surface area is a strong driver on total skin friction drag of an aircraft. Therefore, a first-order estimate of skin friction chargeability can be established by simply assigning skin friction drag chargeability according to the wetted area of each functional component. In effect, skin friction drag would be partitioned according to the proportion of total wetted area contributed by each component. The result will likely be a rather crude estimate of chargeability, but may be accurate enough for analysis at the conceptual or even preliminary design levels.

This approach has the merit of being simple and physically intuitive to use. However, it does not account for the effect of Reynolds number on skin friction coefficient, or the impact of flow separation (the so-called form factor), nor does it make a distinction between laminar and turbulent flow. A more accurate way to determine skin friction drag chargeability (and zero-lift drag chargeability, for that matter) is to outright calculate skin friction drag for each component of the aircraft using any of a variety of available analysis codes. Naturally, this is more complicated than a simple proportionality rule, but can be much more accurate. Since detailed drag data is usually available, this is likely the most convenient means to define drag chargeability in an industrial setting. The appeal of this concept is that it gives designers the ability to explicitly assign a “cost of wetted surface area” in the form of drag loss chargeability.

Wave Drag Chargeability

Wave drag is defined as inviscid drag force created as the result of shock losses in supersonic flow around a body. Wave drag is primarily driven by the total volume distribution of the aircraft, and it is the average of the cross-sectional areas along Mach plane slices integrated over the length of the body that determines wave drag.⁶ This was the fundamental realization that led to fuselage area-ruling and was the genesis for computational methods such as Harris’ well known far-field wave drag algorithm.⁷

However, it is not only the volume of each component (wing, fuselage, tails, etc.) that contributes to wave drag, but the interaction between components. In fact, it is not inaccurate to say that strong mutual interactions between components are the defining characteristic of wave drag. One simply cannot evaluate part of the vehicle wave drag; it is all or nothing. Since the objective of this subsection is to determine rules to define wave drag chargeability, the fundamental question is how to divide wave drag amongst the various airframe components in a physically meaningful way in spite of the presence of strong mutual interference?

The approach used to assign wave drag chargeability in this analysis is to divide the total aircraft wave drag according to the fraction of total volume contributed by each component. For instance, if the wing constitutes 45% of the total volume of the aircraft, then it would receive chargeability for 45% of the total vehicle wave drag. This approach has the advantages of being simple to use and physically reflective of the fundamental mechanisms driving wave drag.

However, as previously mentioned, simple division of wave drag proportionate to component volume takes no account of the way that a particular component’s volume distribution contributes to the entire wave drag of the vehicle. In fact, the only case in which it is completely accurate to partition wave drag strictly according to volume is if the vehicle were a Sears-Haack body. Consequently, the volume proportionality rule for distribution of wave drag chargeability implicitly assumes that the vehicle’s total volume distribution is approximately comparable to a Sears-Haack body. This assumption is reasonably accurate for most modern supersonic aircraft because the stream-wise change in cross-sectional area for this type of aircraft is *tailored* for minimum wave drag during supersonic flight, which drives volume distribution towards a Sears-Haack shape.

The beauty of this concept is that it gives designers the ability to explicitly define the “cost of volume” in terms of increased aerodynamic loss. The impact of volume on vehicle aerodynamic performance is something that designers always implicitly account for, but never explicitly enumerate as part of the analysis process. Moreover, the approach suggested here is based on physical principles and is simple to implement.

Induced Drag Chargeability

Induced drag is defined herein as drag due to the production of lift. Obviously, lift is produced to offset the weight of the vehicle and keep the aircraft in the air. Therefore, one may think of induced drag as an aerodynamic loss caused by the weight of the aircraft, with more weight implying larger loss. Since the vast majority of aircraft flight time is spent in 1-g flight, this is the flight condition of primary interest.

An obvious approach to allocation of induced drag chargeability is to allot it in proportion to the weight of each component of the airframe. For instance, if the wing constitutes 15% of the total aircraft weight at a given flight condition, then wing weight is chargeable for 15% of the induced drag loss at that flight condition. Likewise, if fuel weight constituted 25% of vehicle weight, then 25% of the induced drag loss is chargeable to the weight of the fuel, and so on. Note that induced drag loss is a function of total vehicle weight, so it changes continuously throughout the mission as fuel is burned and stores are expended. This is a very simple and straightforward means of assigning chargeability for induced drag and will be used later in the F-5E example.

Incidentally, since the basic function of the wing is to lift the weight of the aircraft, one could argue that at least part of the zero-lift drag of the wing should also be chargeable to the weight of the aircraft. To better understand this point of view, consider the case of an airship. Since its net weight is zero, it needs no wings to keep it aloft, and since it has no wings, there is no zero-lift skin friction drag associated with the wings. The same argument can be made for an aircraft: a zero weight aircraft would have no need for wings, so all aerodynamic loss due to the wings must ultimately be chargeable to the weight of the vehicle. One could also argue that wing skin friction is driven by the size of the wing, which is in turn driven by the maneuver requirements placed on the vehicle. Therefore, maneuver requirements are in some sense chargeable for wing skin friction drag. Subscription to any of these arguments depends largely on one's point of view. Therefore, the definition of loss chargeability cannot be fixed, but must dynamically change to suit the needs of the particular study of current interest.

Interference Drag Chargeability

Although interference drag will not play a significant role in the analysis of the F-5E, it is worth some consideration given its importance to total drag of other vehicles, notably commercial transports. Allocation of interference drag chargeability is one of the more difficult obstacles to definition of practical and accurate loss management models. This is because definition of interference drag chargeability is inevitably somewhat arbitrary in that it has no clearly and indisputably defined source. By definition, it is drag caused by mutual interference between two bodies, and it is therefore

difficult to determine exactly how much each body is contributing to the mutual interference.

To understand this, consider a simple example of wing-body interference (the most common source of interference drag). W-B interference drag is due to the mutual interaction of the flowfields produced by the wing and the body. If one desires to assign chargeability for this component of drag, the question naturally arises: how much of the drag is chargeable to the wing and how much is chargeable to the body? There is no clear-cut answer, and the choice will certainly depend upon one's point of view.

Lacking any better means of determining interference drag chargeability, it is best to allocate all of it to the body that has the greatest "room to move," that is to say, the body which can most easily be modified to accommodate reductions in interference drag (usually, this is the fuselage or the nacelle for transport-type configurations). Note that this is intended as a suggestion and is certainly not applicable to every situation encountered in vehicle aerodynamic analysis. The exact approach will depend greatly on the circumstances and the judgement of the analyst doing the work.

Miscellaneous Drag Chargeability

This paper has thus far explicitly addressed methods for assigning chargeability for skin friction, wave, induced, and interference drag. These components of drag are the biggest contributors, but there are other components of drag that are significant as well. These include excrescence drag, protuberance drag, pressure drag, trim drag, etc. Generally, the definition of chargeability for these various components must be treated on a case-by-case basis. Ideally, one would like to treat them using detailed aerodynamic analysis methods to estimate total drag, and then assign chargeability based on whatever attribute is the primary driver on that component of drag. For instance, protuberance drag is due to the various appendages that protrude from the basic vehicle mold lines such as antennas, pitot-static tubes, etc. Chargeability for this component of drag is best assigned to the various vehicle systems. Once again, the chief guides in determining chargeability are the designer's intuitive understanding of the primary drivers and the purpose of the analysis. The basic drag chargeability rules devised in the previous three sections are summarized in Table 1.

Table 1 Summary of General Rules for Assignment of Drag Chargeability.

<i>Component</i>	<i>Primary Driver</i>	<i>Chargeability Rule</i>
<i>Skin Friction</i>	<i>Wetted Area</i>	<i>Estimated per Component</i>
<i>Wave Drag</i>	<i>Vehicle Volume</i>	<i>Proportional to Comp. Volume</i>
<i>Induced Drag</i>	<i>Vehicle Weight</i>	<i>Proportional to Comp. Weight</i>
<i>Interference</i>	<i>Mutual Intractn</i>	<i>Comp. W/ Dsgn Flexibility</i>
<i>Misc. Drag</i>	<i>Various</i>	<i>Charged on Case-by-Case Basis</i>

Application to the F-5E

Up to this point, this paper has concentrated on developing the basic theory and mechanics for defining aerodynamic loss chargeability for aircraft. The objective of this section is to provide a practical example of the concepts introduced in this paper by demonstrating them on the Northrop F-5E. This section will begin with a description of the analysis method used to create the F-5E aerodynamic loss deck. This analysis model is then used to develop an aerodynamic loss deck shown in a series of “loss envelopes” similar to a typical flight envelope. The results from this analysis are discussed in detail.

Analysis Method

The analysis method used to generate the aerodynamic loss deck for the F-5E is represented in Fig. 1. Since aerodynamic loss analysis is non-standard in the vehicle preliminary design world, there were no ready-made analysis codes that could be used to estimate aerodynamic loss. Therefore, the analysis tools and methods were developed “from scratch.”

The approach taken herein was to develop an algorithm to post-process results from standard aerodynamic analysis codes. The loss analysis tools used herein consist of two simple routines linked to a spreadsheet-style analysis. Each routine has a particular analysis function, the first being to estimate zero-lift drag (C_{D0}) at all flight conditions, and the second to estimate induced drag (C_{Di}) for 1-g level flight as a function of flight condition and vehicle weight. Both require drag data and a vector of flight conditions at which to evaluate drag coefficient. The drag data used herein was taken directly from Northrop drag reports for the F-5E.^{8,9,10}

Output from these routines is then used in conjunction with a scheme for aerodynamic drag chargeability that allows C_{D0} to be broken into its constituent parts. This is then used to calculate power required to overcome each component of drag at every flight condition and vehicle weight, and constitutes an F-5E aerodynamic loss deck.

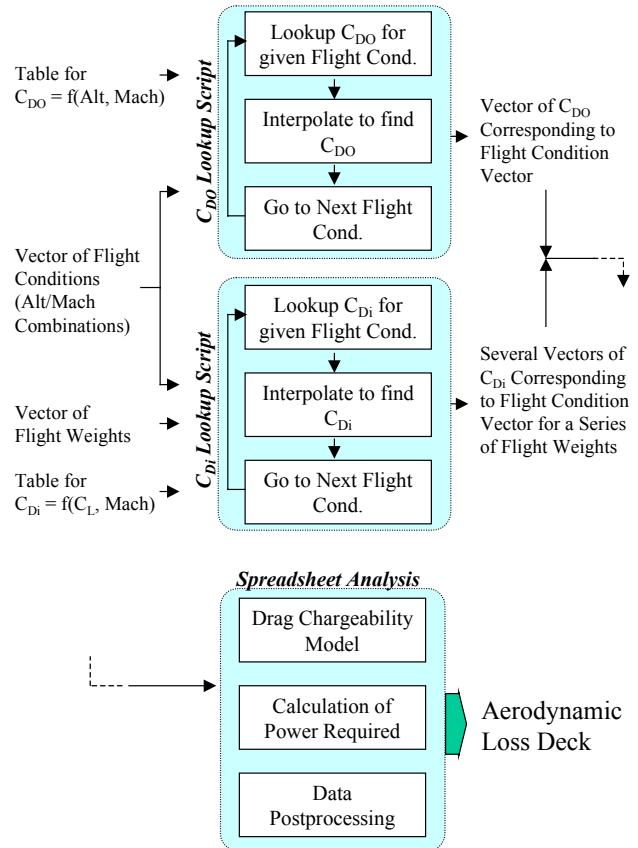


Fig. 1 Aerodynamic Loss Analysis Method for Construction of F-5E Loss Deck.

F-5E Aerodynamic Loss Deck

Since the F-5E is not capable of sustained supersonic cruise, aerodynamic loss is taken to be equal to the drag work done by the vehicle on the atmosphere, given by Eq. 1. It is relatively simple to use this definition of loss in conjunction with the drag envelope data calculated from analysis scripts to evaluate total drag work for every flight condition, the results of which are shown in Fig. 2. This total drag was subsequently broken into six major components, shown in Fig. 3. These are: stores drag, horizontal and vertical tail drag, wing drag, fuselage drag,

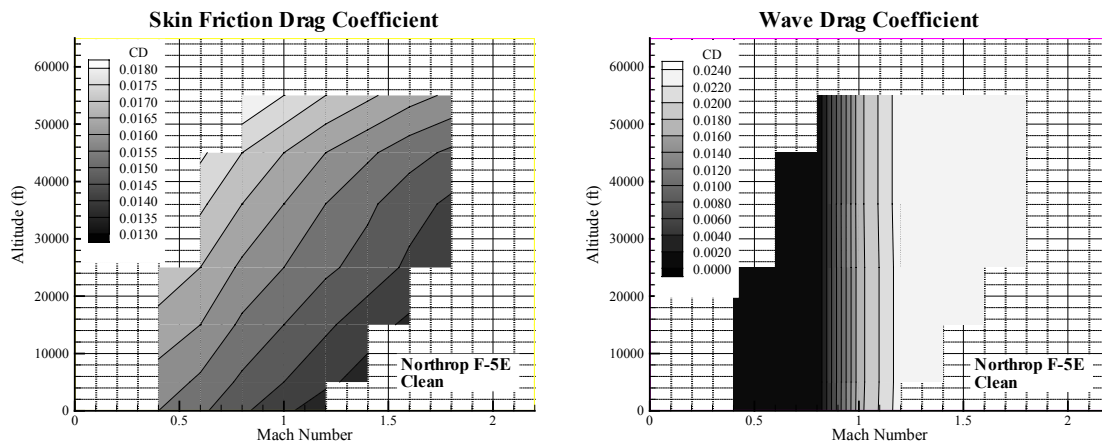


Fig. 2 F-5E Zero-Lift Drag Coefficient as a Function of Flight Condition.

and induced drag (trim drag is ignored in this analysis).

One difficulty encountered in creating an F-5E aerodynamic loss deck is that the manufacturer's flight test data upon which this analysis is based gives only *total* drag and does not give any information as to the individual drag components that make it up. However, most drag components are easily identified and separated from total drag. First, induced drag is separated from zero lift drag. Next, wave drag is relatively easy to separate from all other zero-lift drag. Ostensibly, the remaining drag is predominantly due to skin friction.

Skin friction drag chargeability was determined using an aerodynamic analysis code.^{11,12} In general, this estimate will not be an exact match to the actual skin friction drag known from flight test data. However, the *relative proportion* of component-wise skin friction drag estimated by the analysis code should be relatively accurate. The relative proportions can therefore be used to define drag chargeability of the actual vehicle by allocating the known flight test drag in proportion to the analyzed drag (as shown in Table 2).

Chargeability for the wave drag of the four major aircraft components was distributed in proportion to component volume. Stores drag and induced drag are explicitly known from test data. F-5E drag chargeability is summarized in Table 2.

Based on this drag breakdown, a series of 14 loss envelope plots were generated for aerodynamic drag loss. These loss envelopes depict drag loss (power required) as a function of flight condition. Fig. 4 shows an overview of total power required for skin friction drag and wave drag. It is clear from these plots that wave drag is negligible in the subsonic regime, but quickly becomes dominant in the supersonic regime.

Table 2: Summary of F-5E Drag Chargeability.

Drag Component	Fuselage	Wing	H Tail	V Tail
Skin Friction	45%	34%	11%	10%
Wave Drag	76%	17%	4%	3%
Induced Drag	N/A	Known	N/A	N/A
Store Drag (AIM-9J)	N/A	N/A	N/A	N/A

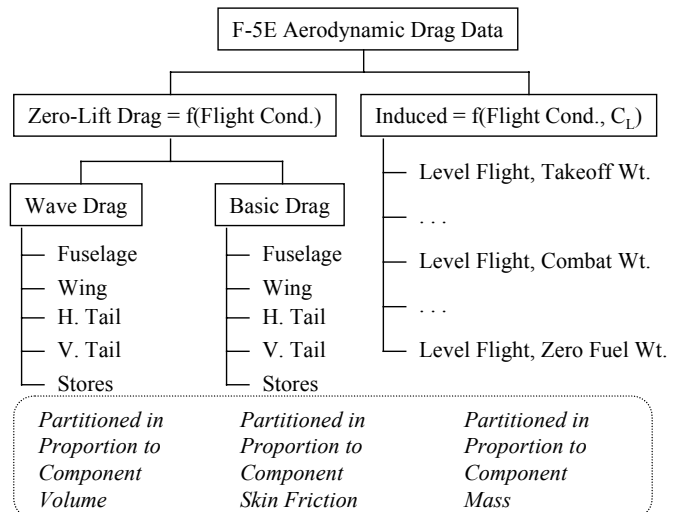


Fig. 3 Breakdown of Aerodynamic Drag Chargeability for the F-5E.

These two plots can be further decomposed according to drag power required due to each of the major components. Fig. 5 shows the distribution of wave drag chargeability amongst the fuselage, wing, and tails. As one would expect, the fuselage is by far the dominant contributor, due to its volume. Likewise, Fig. 6 shows the distribution of skin friction drag amongst the major components. Once again, fuselage drag is the largest contributor, but wing drag makes a comparable contribution. Note that the power required contours for these plots are strongly driven by flight velocity.

The last four plots of Fig. 7 show loss due to stores drag and loss due to induced drag at 1-g level flight (for 3 aircraft weights: 16,000 lb, 13,200 lb, and 10,000 lb). Note that induced drag loss for 1-g level flight shows a “minimum loss corridor”. This behavior is quite counterintuitive given that one usually expects induced power required to decrease monotonically with increasing speed. The unexpected increase in induced power at high speed is due to camber in the F-5E wings and fuselage,

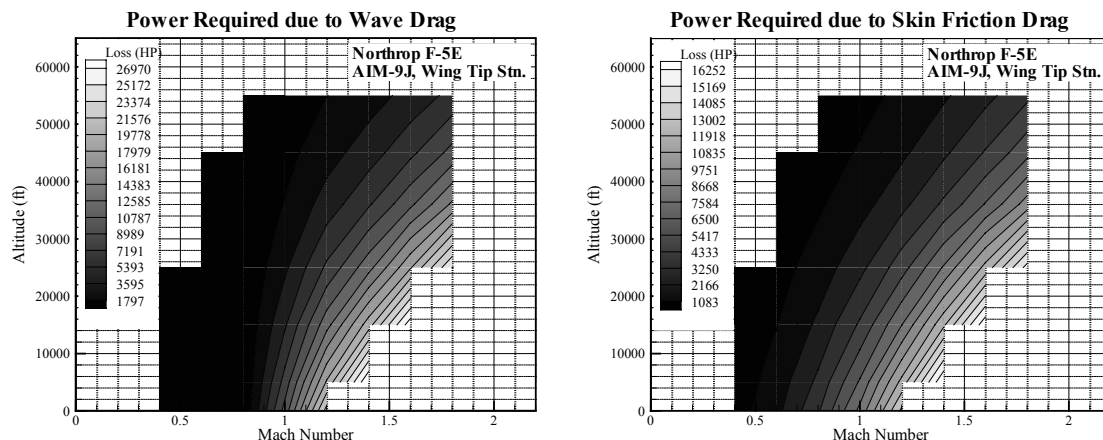


Fig. 4 Aerodynamic Loss Envelopes Showing F-5E Total Power Required.

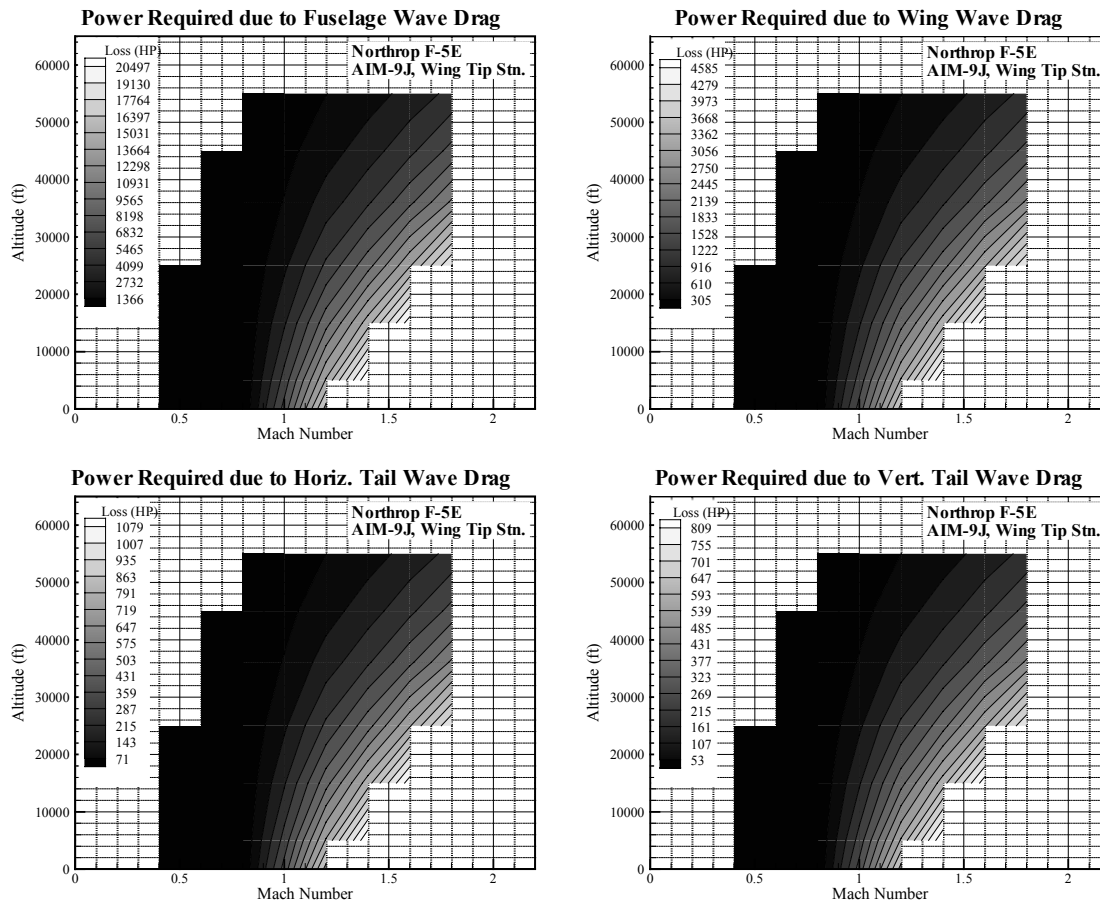


Fig. 5 Aerodynamic Loss Envelopes for F-5E Wave Drag.

which results in the zero lift angle of attack being slightly negative. This forces the aircraft to fly at a very small or even slightly negative angle of attack to maintain level flight at very high dynamic pressure, resulting in increased induced drag.[§]

This set of plots is sufficient to completely characterize the aerodynamic losses of the Northrop F-5E at any flight condition. Collectively, these charts constitute an “aerodynamic loss deck” sufficient for preliminary design analysis. This deck is quite useful for comparing relative magnitudes of loss at any flight condition. It also gives a broad and intuitive feel for the aerodynamic drag power required for the Northrop F-5E.

Integration of Aero Losses for the Design Mission

The loss deck has broader (and arguably more important) use than has hitherto been discussed. Specifically, this deck can be used in conjunction with a mission time history to obtain total loss attributable to each loss mechanism integrated over the entire mission. Once the aero loss deck is available, integration of losses

through the mission amounts to recursive summation of a table lookup for each loss mechanism and every timestep in the mission time history. It is the integrated loss through the design mission that truly drives fuel consumption and vehicle size, so it is the integrated loss that is of greatest interest from a design perspective.

The usefulness of this type of information can easily be illustrated using the F-5E example studied herein. The F-5E design mission is a simple subsonic area intercept of 450 nmi range. This mission consists of a maximum power takeoff, climb, subsonic cruise out to the combat zone, 5 minutes allowance at M1.3 50,000 ft maximum power for combat (no range credit), followed by a subsonic return cruise and 20 minute reserve loiter plus 5% fuel reserve. Basic airframe, engine, and mission parameters are summarized in Table 3.

Table 3 Vehicle and Mission Assumptions.

Basic Load:	(2) AIM-9J, Wing Tip Stn, 394 lb Ammunition 4,501 lb Internal Fuel (4,400 lb Mission Fuel)
Aircraft:	Takeoff Gross Weight = 15,633 lb Fixed Empty Weight Wing Area = 186.2 ft²
Engine:	(2) J85-GE-21 @ 5,000 lbf Thrust ea.
Assumptions:	All Cruise @ Best Alt/Mach 5% Fuel Flow Conservancy, 5% Reserve Fuel 450 nmi Range

[§] Note also the loss contours are slightly erratic at high dynamic pressure. This is due primarily to rounding and interpolation errors on induced drag coefficient (C_{Di}) at high speed: C_{Di} is on the order of 6 ct while the error is on the order of 3ct. Considerable precision on C_{Di} is required to accurately calculate induced loss at high dynamic pressure flight conditions.

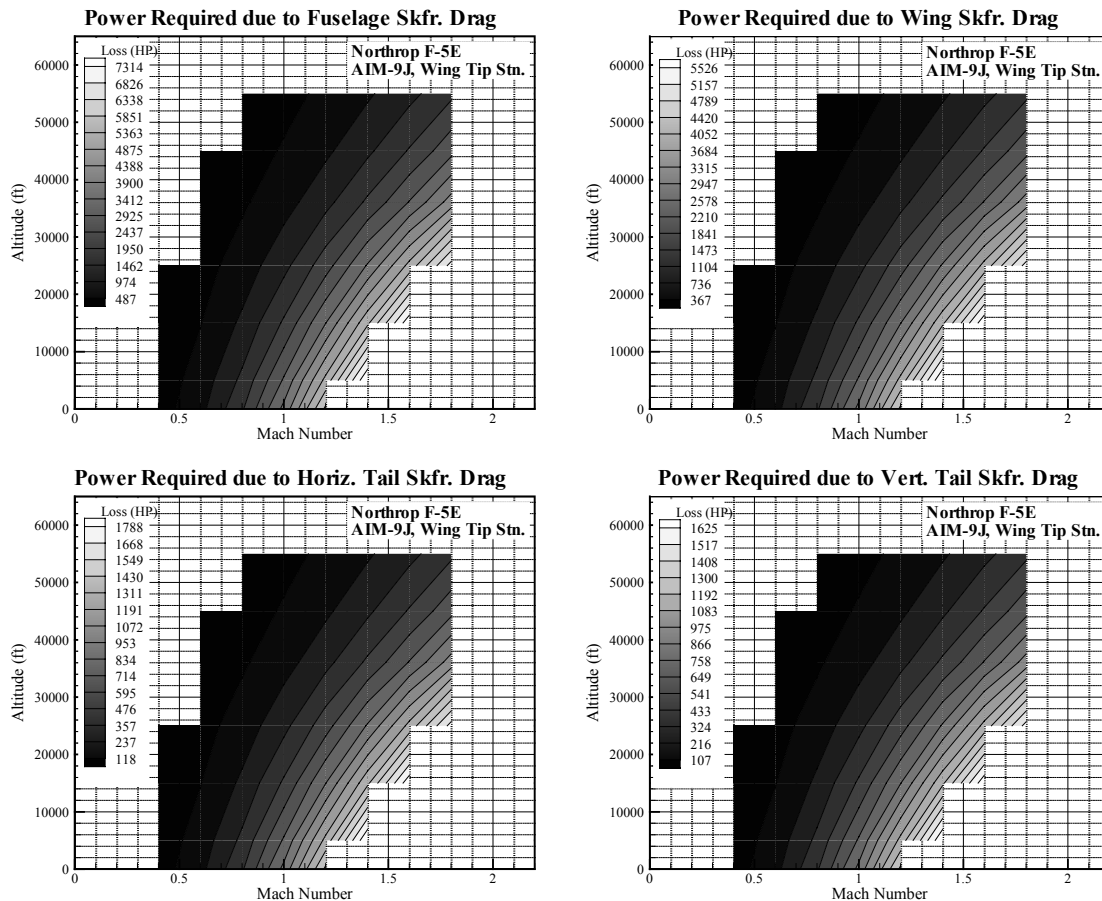


Fig. 6 Aerodynamic Loss Envelopes for F-5E Skin Friction Drag.

This mission can be analyzed using standard mission analysis codes¹³ and techniques to obtain a mission time history. If this time history is used to integrate aerodynamic losses throughout the mission, the result is as shown in Fig. 8. This figure shows mission time history versus power required for each aerodynamic loss mechanism present during the design mission. The various loss mechanisms shown in this plot are ‘layered’ on top of one another, and the mission legs are annotated along the top. Fig. 8 shows that the maximum power required is during the climb and supersonic dash legs, due primarily to the additional wave drag present for this flight condition. However, total drag work is the area under each curve, and it is evident from this figure that skin friction drag on the various components constitutes a considerably larger area on this plot than does wave drag.

Discussion of Results

If the area under each curve in Fig. 8 is integrated to obtain total drag work over the entire mission, the results are as shown in Table 4. This shows a breakdown of drag according to drag mechanism and component for the F-5E. In addition, total loss of thrust work potential^{14,15} due to engine inefficiencies is shown for comparison.

It is interesting to note that roughly 40% of the thrust work potential initially present in the mission fuel is lost

due to inefficiencies in the propulsion system. The remaining thrust work potential is converted into thrust work by the engines. Essentially all of this thrust work is used to overcome vehicle drag, with a miniscule amount going to power the various systems installed aboard the F-5E. Of the aerodynamic losses, skin friction, induced drag, and wave drag constitute 28%, 24%, and 7%, respectively. The remaining 2% of thrust work potential is used to overcome stores drag. The relative proportions of these loss mechanisms clearly show that skin friction and induced drag are the dominant mechanisms, with wave drag playing a relatively minor role. Obviously, if the F-5E mission had been a short range, maximum speed intercept then the relative loss proportions would have been considerably different.

Table 4 suggests that one should be willing to trade reductions in wave drag at a 4-1 rate with reductions in skin friction drag. Similarly, one should trade reduction in wave drag at a 3-1 rate with weight reduction and a 5-1 rate with propulsion improvements. Skin friction should be traded at a 1-1 rate with weight reduction and a 1.35-1 rate with propulsion improvements. Finally, one should trade reduction in weight at a 1.5-1 rate with propulsion improvements. It must be understood that these trade ratios are predicated on two important assumptions. First, the total work potential estimates are based on a

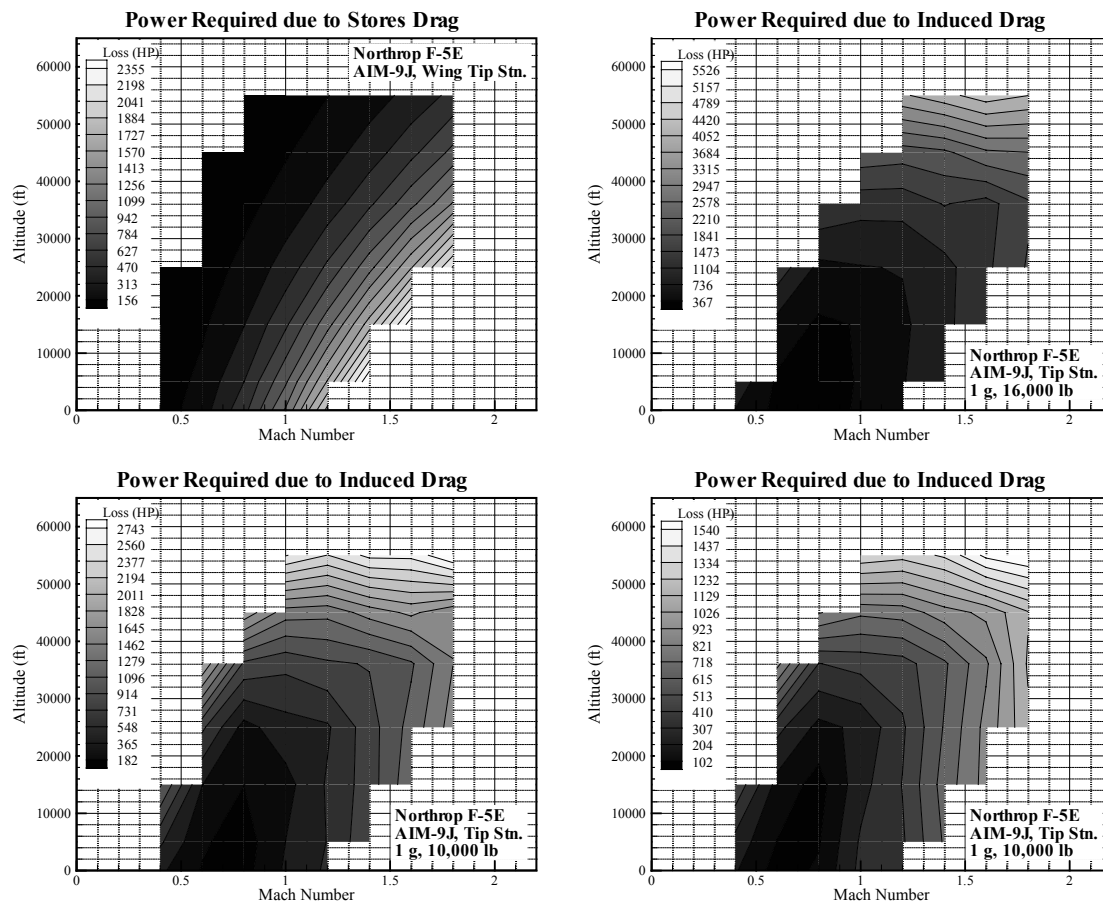


Fig. 7 Aerodynamic Loss Envelopes for F-5E Induced and Stores Drag.

thrust work potential metric, which is only one of several work potential figures of merit that can be used. Second, the reductions must be taken on a *mission-integrated* basis. For example, a 1% reduction in skin friction drag at a given flight condition is irrelevant. However, a 1% reduction in skin friction drag work *integrated over the mission* can be traded for 4% reduction in wave drag, or a 1% weight reduction, etc.

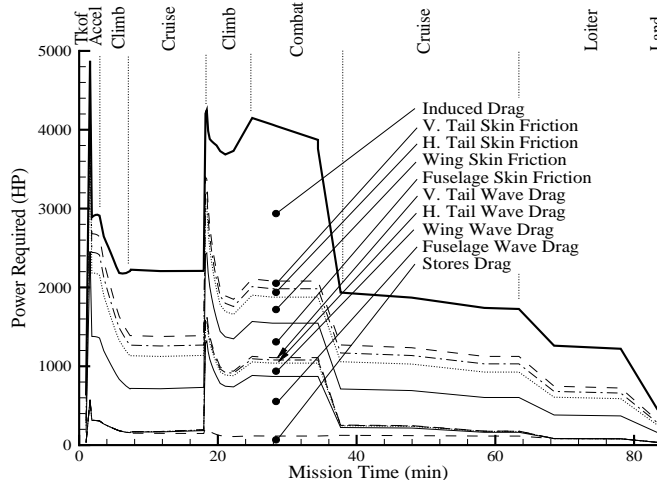


Fig. 8 Aerodynamic Drag Work During F-5E Area Intercept Mission.

Table 4: Total Loss Integrated Over the F-5E Aera Intercept Mission.

Component of Work Usage	Work	Work
	Potential (HP-min)	Potential (% Total)
Total Propulsion System Losses	113,762	37.3%
Thrust Work Produced	191,529	62.7%
Aerodynamic Drag Loss		
Wave Drag	Fuselage Wave Drag	17,226 5.6%
	Wing Wave Drag	3,852 1.3%
	Horizontal Tail Wave Drag	901 0.3%
	Vertical ail Wave Drag	682 0.2%
	Total Wave Drag Loss	Σ= 22,661 7.4%
Skin Friction	Fuselage Skin Friction	37,925 12.4%
	Wing Skin Friction	28,652 9.4%
	Horizontal Tail Skin Friction	9,268 3.0%
	Vertical Tail Skin Friction	8,417 2.8%
	Total Skin Friction Drag Loss	Σ= 84,262 27.6%
Mass Properties	Loss Due to Structure Weight	26,052 8.5%
	Loss Due to Propulsion Weight	9,116 3.0%
	Loss Due to Fixed Equip. Weight	9,572 3.1%
	Loss Due to Stores Weight	3,466 1.1%
	Loss Due to Fuel + Misc. Weight	26,061 8.5%
Induced Drag Loss		Σ= 74,267 24.3%
Stores Drag Loss		5,446 1.8%
Total Drag Loss		186,636 61.1%
Total Loss in All Vehicle Systems/Subsystems		305,291 100.0%
Net Work Stored in Vehicle Potential Energy		0
Net Work Stored in Vehicle Kinetic Energy		0

Up to this point, it has been shown that approximately 28% of the total F-5E drag work (and therefore 28% of total mission fuel) is due to skin friction on the various components. Similarly, 24% of mission fuel is chargeable to the empty weight of the various components, and 7% is chargeable to the volume of these components. This information can be used to define chargeable gross weight of every component in the airframe, as explained in Ref. 1. For example, the empty weight of the F-5E wing is 1,315 lb. This weight must be lifted through the atmosphere, thereby implying an induced drag loss. This loss is equivalent to 127 lb of mission fuel. Likewise, 478 lbs of mission fuel is required to offset wing skin friction and wave drag. In some sense, then, the wing's contribution to total airframe gross weight is roughly 1,921 lbs. A similar exercise can be used to find the chargeable gross weight of all weight groups.

The above example is intended to show that chargeable gross weight gives a more accurate reflection of a component's total contribution to the whole than do conventional weight management methods. One could therefore argue that airframers would be better served if they were to use chargeable gross weight as the primary metric for allocating group weight in their weight management plans. Moreover, the method defined here is very general and is therefore applicable to any number of platforms: ships, subs, airships, rockets, cars—any vehicle whose design is strongly driven by thermodynamic losses.

Conclusions

The intent of this paper has been twofold: to develop a rudimentary theory for definition of aerodynamic loss, and to develop basic concepts and ground rules for definition of drag loss chargeability. These concepts were then used to construct an aerodynamic loss deck for the F-5E. To this author's knowledge, this is the first time a *comprehensive* loss deck such as this has been constructed, and it required the development of several simple analysis tools and methods to realize. Furthermore, it has been shown that aerodynamic loss decks are useful not only for determining the relative magnitudes of aerodynamic losses, but also suited for use in loss management models of the entire aircraft.

It should be noted that this analysis has only attempted to capture "first order" effects for chargeability. Inclusion of second order effects requires much more detail and yields only a small improvement in model accuracy. In addition, second order effects are more subjective than first order effects. Therefore, this is left as a subject for future investigation.

This paper has focused on showing how the concept of loss chargeability is useful to analysis of aircraft aerodynamic performance. However, it is important to understand that aerodynamic loss chargeability is even more useful when applied as part of a larger system-wide

analysis of the whole aircraft. This is the driving idea behind the concept of the loss management model, which requires allocation of *all* losses integrated throughout the mission. The soundness of the loss management model concept hinges upon the ability to clearly and unambiguously define drag chargeability.

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